3D-Printable Prosthetic Foot with Human Toe-Joint Property

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RESEARCH HIGHLIGHT

- Design the 3D-printable prosthetic foot with human toe-joint property within yield strength of materials
- Compare the stiffness characteristics of the prosthetic foot with respect to the auxetic structures

INTRODUCTION

Human toe-joint property

- In the gait cycle, human foot has variable stiffness characteristics [1] as shown in Fig. 1.
- One of the critical factors is the toe joint stiffness which has not been considered in the prosthetic foot design so far.
- Therefore, in designing the prosthetic foot, the gait biomechanics of the human toe joint must be considered to have human-like ambulation.

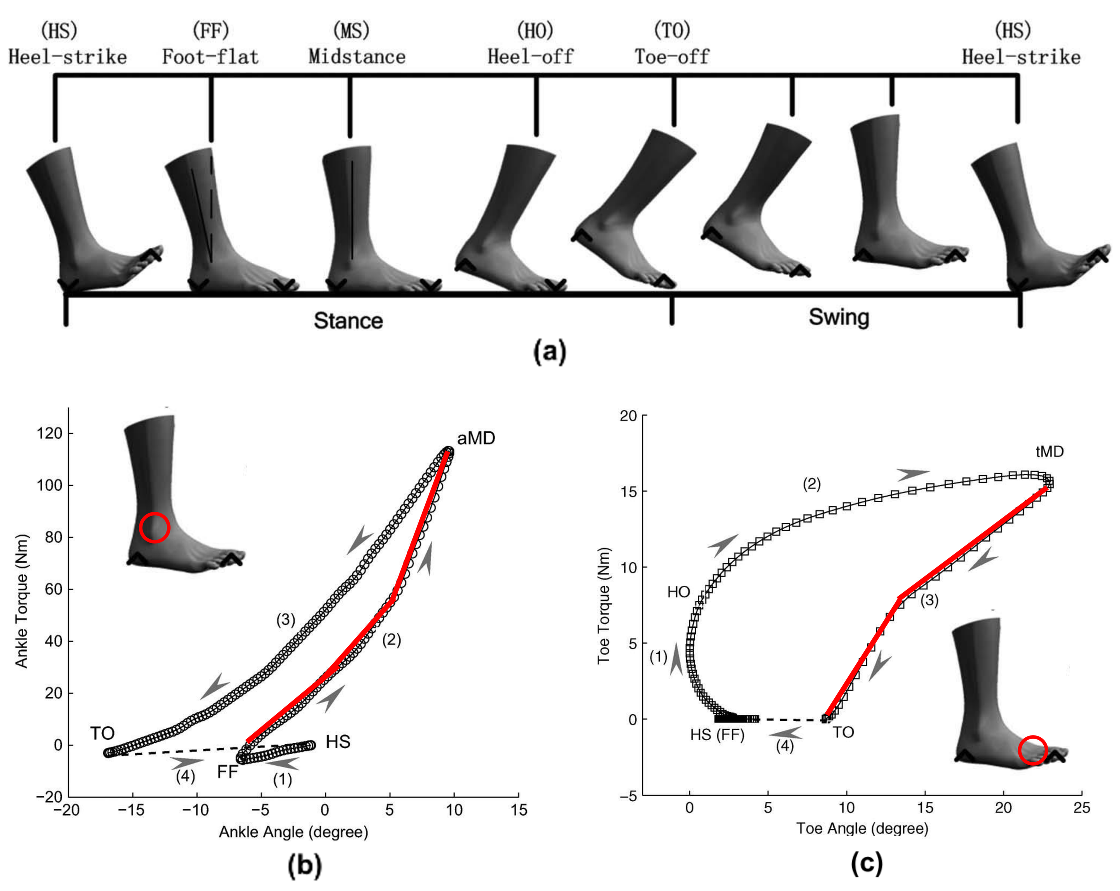

Fig. 1 (a) The schematic of the human gait cycle and the stiffness characteristics (slope of torque-angle graph) of the (b) ankle and (c) toe.

Prosthetic foot with variable toe stiffness

- A few studies have attempted to implement the toe stiffness in the prosthetic foot design; however, their designs were complex to be manufactured [2], [3].
- Also, the aforementioned designs usually require an additional mechanical part for the toe joint, leading to the heavier foot.
- In this study, we propose the 3D printable foot structure (i.e., re-entrant and honeycomb structure [4]) to mimic human foot characteristics, specifically the toe stiffness.

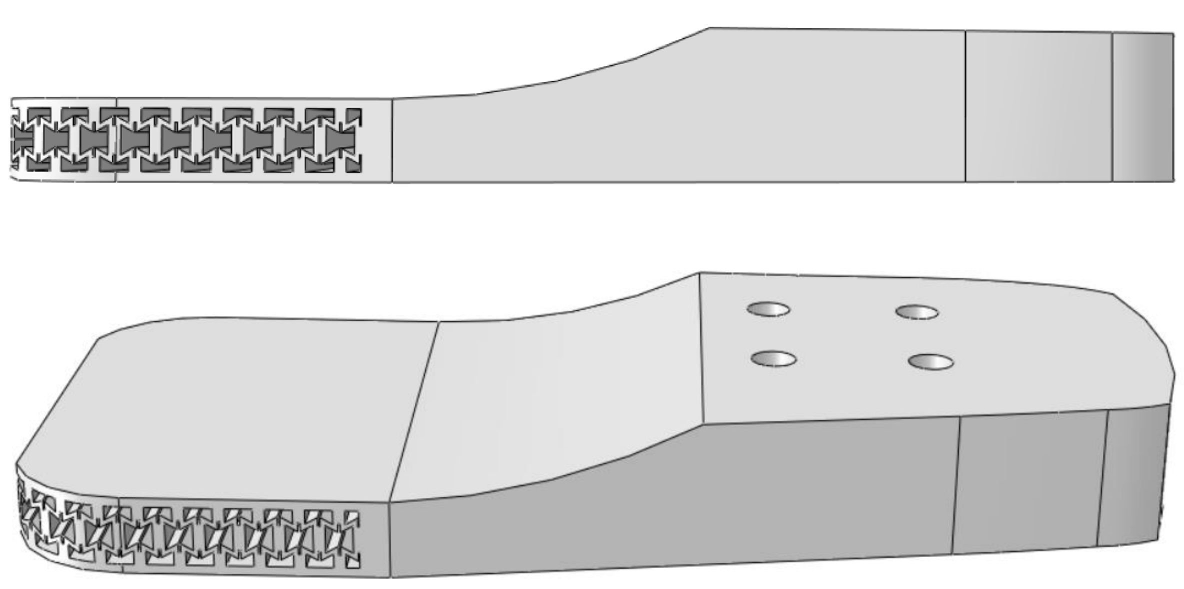

Fig. 2 3D-printable prosthetic foot design.

EXPERIMENTAL SETUP

Composite material

- In general, the ABS is used for the 3D printing material.
- However, in this study, a composite material, called "onyx", was proposed to enhance the elasticity and strength.
- Onyx is rigid nylon in combination with micro-carbon fiber (Fig. 2(a)), which has high strength, light weight and flexibility.
- To investigate the effect of the foot material, two different materials (i.e., ABS and onyx) were compared.

Auxetic structure

- Auxetic structures are resistant to deformation because they reduce stress when deformed.
- Also, they have variable stiffness characteristics when deformed.
- In this study, two auxetic structures (i.e., re-entrant and honeycomb structure) were examined in the design of the toe for the compliance and variable stiffness.

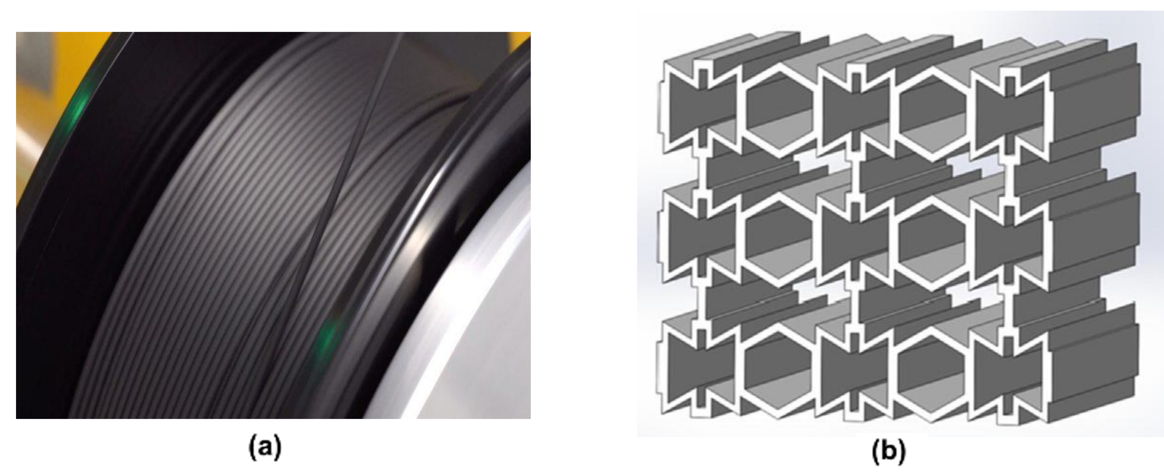

Fig. 3 (a) composite material called "onyx" and (b) auxetic structure (the figure represents combined structure of the re-entrant and honeycomb)

Simulation model

- To analyze the toe stiffness properties, two finite element analysis (FEA) models (a: re-entrant, b: re-entrant honeycomb) were established (Fig. 4)
- In Fig. 4(a), the re-entrant structure was applied in the forefoot, and two different materials (i.e., ABS and onyx) were compared using the identical structure in the simulation to investigate the effect of the foot material.
- Furthermore, in Fig. 4(b), the combined structure of the re-entrant and honeycomb was applied in the forefoot to release stress concentration of the re-entrant model.
- Then, to analyze toe bending characteristics, a simulation was conducted with and without the bending zone (BZ) in Fig. 4(b).

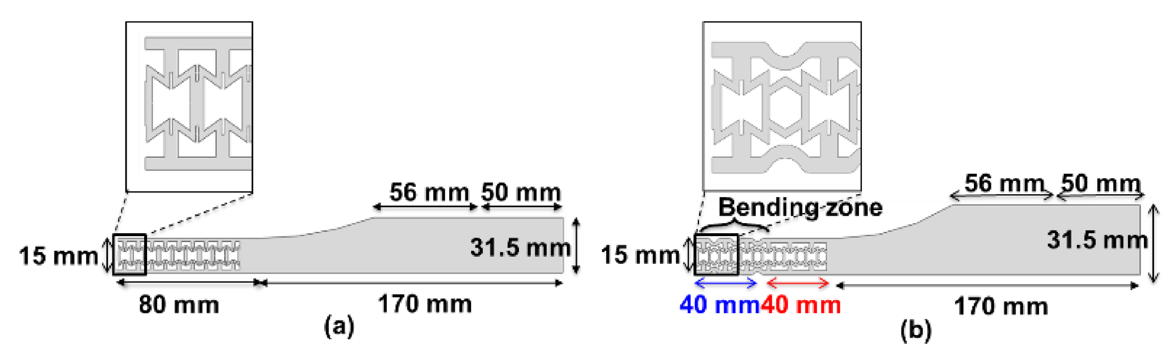

Fig. 4 FEA models. (a) The re-entrant structure was applied in the forefoot; (b) the combined structure of the re-entrant, honeycomb, and BZ was applied in the forefoot

Simulation setup

- All numerical simulation was done with ABAQUS (v6.14, ABAQUS Inc., Vélizy-Villacoublay, France).
- For a toe bending simulation, a rigid plate was placed at the bottom of the forefoot and approached gradually to the re-entrant model that was inclined with 10°.
- In the re-entrant honeycomb model, the rigid plate was approached gradually with 15° angle with the model to confirm reinforcement of the latter model.
- Fig. 5 depicts initial state (Fig. 5(a), Toe-off) and the final state (Fig. 5(b), Heel-off) of the prosthetic foot in the simulation. Please note that the simulation was performed in the reverse order of the gait cycle due to the loading condition in simulation.

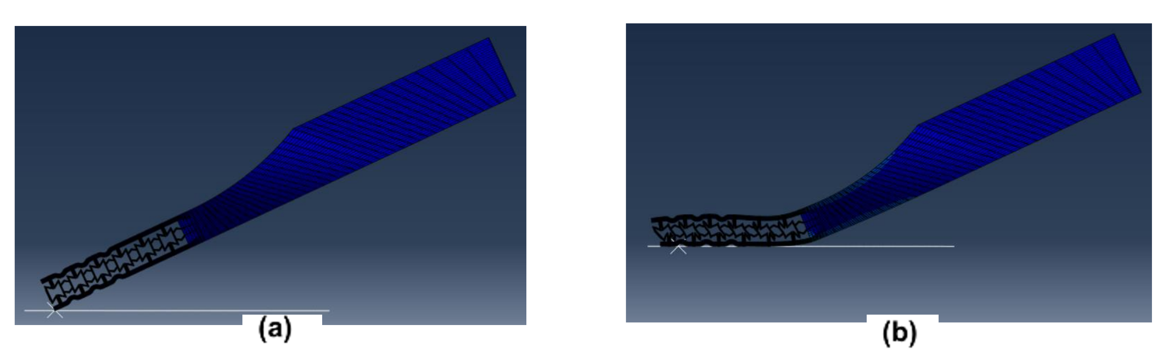

Fig. 5 Toe bending simulation; (a) initial state of prosthetic foot which represents Heel-off step and (b) final state of prosthetic foot which represents Toe-off step.

RESULTS AND DISCUSSION

- The Fig. 6 shows the FEM results of the re-entrant model.
- The stiffness (i.e., slope of F/D curve) of the onyx increased while that of the ABS was constant as shown in Fig. 6(a).
- The nonlinearly increasing toe joint stiffness is desired for the prosthetic foot due to the human gait biomechanics.
- In addition, the onyx showed lower maximum stress and higher yield strength than the ABS (Fig. 6(b)).
- Since the onyx has high elasticity and strength, it may have performed variable stiffness characteristics while having a proper strength characteristic.

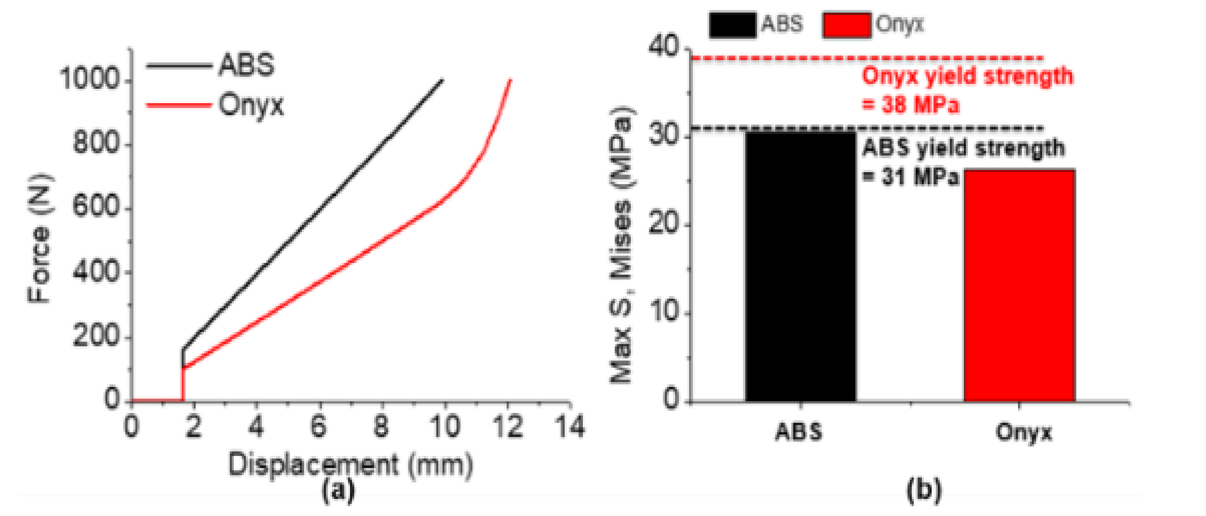

Fig. 6 The FEA results of the first model: re-entrant structure (a) F-D graph; (b) maximum stress

- The re-entrant honeycomb model was designed to reduce the maximum stress since the maximum stress of the re-entrant structure exceeded the yield strength when the toe bending angle was over 15°.
- As it resulted in a deterioration of the stiffness characteristics, BZ was used to compensate it.
- The FEA results are depicted in Fig. 7 and the characteristics of the stiffness and the strength were enhanced when the BZ is considered
- The curved surface of the BZ released the stress concentration, resulting in the enhancement of the bending characteristics.

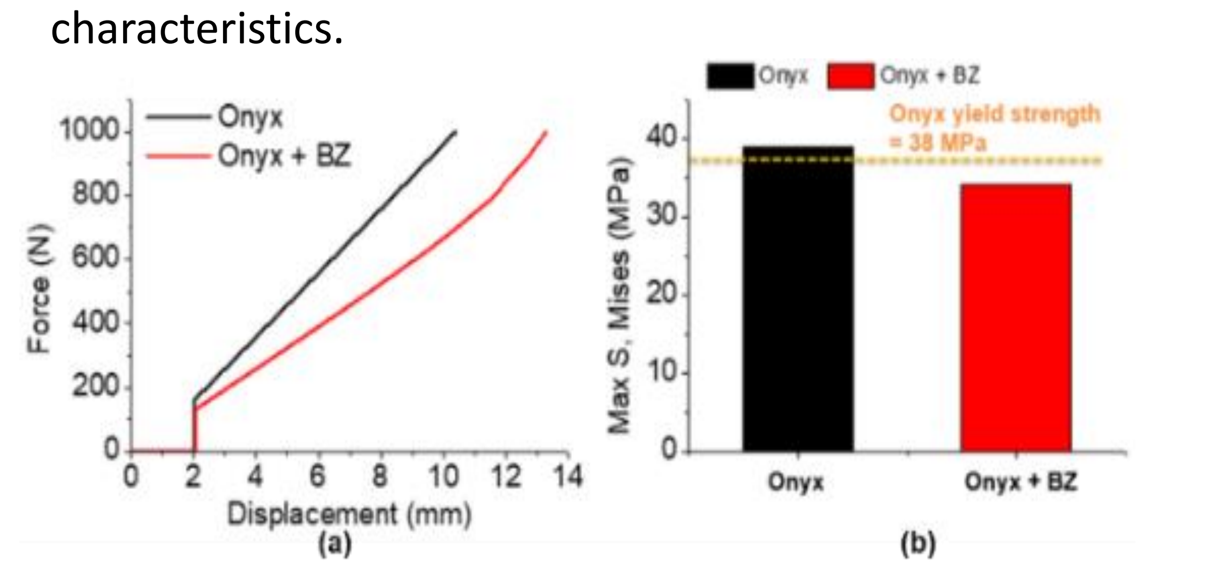

Fig. 7 The FEA results of the second model: re-entrant honeycomb structure (a) F-D graph; (b) maximum stress

CONCLUSIONS

It was observed that

- The variable stiffness characteristics can be implemented using onyx and auxetic structure within the yield strength.
- Bending zone releases stress concentration, reducing the maximum stress and enhancing the bending characteristics.

FUTURE WORKS

- Extract the torque-angle curve from the toe position data and design a structure that replicates the stiffness characteristics of human foot.
- Manufacture the designed prosthetic foot using 3D printer and validate the results with biomechanical experiments.

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